Open heavy flavour with ALICE

A. Rossi (INFN Padova) on behalf of the ALICE Collaboration

12th International Workshop on high-\(p_T\) physics in the RHIC/LHC era
Heavy-flavour with ALICE: main goals

**Pb-Pb collisions**
- Large mass → early formation time
- Creation/annihilation rate in the medium very small
- Production can be calculated with pQCD down to $p_T=0$
- **Ideal probes to study the parton interactions in the medium**
- **Heavy-quark energy loss:**
  - radiative + collisional processes
  - mass and Casimir factor dependence
  - hadronisation via coalescence → enhanced $D_s$ and charmed-baryon yields
- **Heavy-quark azimuthal anisotropy**
  - participation to system collective motion and possible thermalisation (at low $p_T$)
  - path length dependence of energy loss (at high $p_T$)

**pp collisions**
- Reference for p-Pb and Pb-Pb collisions.
- Characterise heavy-flavour production and set constraints to theoretical calculations.

**p-Pb collisions**
- Study cold nuclear matter effects (shadowing, gluon saturation, $k_T$-broadening, energy loss in CNM in the initial and final state)
- Address possible collective effects and effects related to the (possible) formation of a QGP in p-Pb collisions.

More theoretical insight: M. Nahrgang (next talk)
Open heavy-flavour with ALICE

Charmed hadrons ($|y|<0.5$)
Invariant mass analysis of
- $D^0 \rightarrow K^- \pi^+$
- $D^{**} \rightarrow D^0 \pi^+$
- $D^+ \rightarrow K^- \pi^+ \pi^+$
- $D_s^+ \rightarrow \phi \pi^+, \phi \rightarrow K^- K^+$
- $\Lambda_c^+ \rightarrow p K^- \pi^+$
- $\Lambda_c^+ \rightarrow p K^0_s, K^0_s \rightarrow \pi^+ \pi^-$
- $\Lambda_c^+ \rightarrow e^+ \Lambda \nu, \Lambda \rightarrow p \pi^-$
- $(\Xi_b \rightarrow) \Xi_c^0 \rightarrow e^+ \Xi^- \nu_e, \Xi^- \rightarrow \pi^- \Lambda$

HF –decay electrons ($|y|<0.9$)
- $c, b$ hadrons $\rightarrow e X$
- $b$ hadrons $\rightarrow e X$

Beauty-decay $J/\psi$ ($|y|<0.9$)
- $b$ hadron $\rightarrow J/\psi X, J/\psi \rightarrow e^+ e^-$

HF-decay muons ($2.5<y<4$)
- $c, b$ hadrons $\rightarrow \mu X$

Measurements of:
- Single particle production
  - Also vs. event activity (multiplicity, centrality)
- Angular correlations with charged particles
- HF-tagged jets
Recent results in pp collisions

- D⁰, D⁺, D*⁺, D⁺s meson cross section measured at several collision energies
- Down to $p_T=0$ for D⁰ at 7 TeV
- pQCD calculations describe the data within uncertainties
- Data uncertainties much smaller than theoretical ones
Heavy-flavour decay electron cross section at 13 TeV in |y|<0.8

Very precise data to constrain charm and beauty production → input to theorists
Yield of forward HF-decay muons increases with charged particle multiplicity at central rapidity

- Slightly faster than linear increase at high mult.
- $p_T$ dependence under scrutiny

Similar increase for HF-decay muons (2.5<$y$<4) and D mesons ($|y|<0.5$)

Model calculations need to include multiple parton interactions to qualitatively describe the trend (see backup)
Charmed baryons in pp and p-Pb collisions

$\Lambda_c$ production cross section higher than theoretical expectations in pp and p-Pb collisions
Charmed baryons in pp and p-Pb

- $\Lambda_c^+/D^0$ and $\Xi_c^0/D^0$ higher than theoretical expectations (large uncertainties)
  → Is charm hadronisation understood?
  → Need to reduce experimental uncertainties to provide more precise input to models
p-Pb collisions
Non-strange D meson and $D_s^+ R_{pPb}$ compatible with unity.

Described by models including Cold Nuclear-Matter effects.

Described by models including formation of QGP in p-Pb, though data disfavour suppression $>10$-$15\%$ at high $p_T$.

$\rightarrow$ Need to improve precision at low $p_T$ for more conclusive statements

$\rightarrow$ Looking forward to new pp run at 5 TeV
Production vs. centrality

Extension of results in ALICE-PUBLIC-2017-008

\[ Q_{p\text{Pb}}^{0-10\%}(p_T) = \frac{dN_{p\text{Pb}}^{0-10\%}}{dp_T} \times \frac{\langle T_{AA} \rangle_{0-10\%} \times d\sigma_{pp}}{dp_T} \]

Event centrality determined with ZN calorimeters (least biased selection, PRC 91 064905 2015)

- D-meson \(Q_{p\text{Pb}}\) in 0-10% and 60-100% compatible with unity and within each other
- Similar trends than charged particles
Production vs. centrality

Extension of results in ALICE-PUBLIC-2017-008

- Hint for D-meson “Central-to-peripheral” ratio ($Q_{CP}$) larger than unity
  - $1.5\sigma$ in $2<p_T<8$ GeV/c
- Very similar to charged particle $Q_{CP}$
- Similar “bumpy” trend observed for proton and strange-baryon $R_{pPb}$
  - Initial-state effect? Mass effect? Radial flow?
  - … early to say, need comparison with theoretical calculations
In pp and p-Pb collisions no evidence of modification of $D_s^+/D^+$ ratio
Heavy-flavour decay electron $v_2$

- Analysis of “per-trigger” HF-decay electron-hadron azimuthal correlations in 20% collisions with higher multiplicity (selected with V0A, $2<\eta<5.1$)
Heavy-flavour decay electron $v_2$

- Analysis of “per-trigger” HF-decay electron-hadron azimuthal correlations in 20% collisions with higher multiplicity (selected with V0A, $2<\eta<5.1$)
- Subtraction of jet contribution from correlations in 60-100% multiplicity class
Heavy-flavour decay electron $v_2$

- Analysis of “per-trigger” HF-decay electron-hadron azimuthal correlations in 20% collisions with higher multiplicity (selected with V0A, $2<\eta<5.1$)
- Subtraction of jet contribution from correlations in 60-100% multiplicity class
- Positive $v_2\{2,\text{sub}\}$ measured for heavy-flavour decay electrons in $-1.26<y<0.34$
  - Initial-state effects, collective effects?
- Data suggest relevant effect, close to maximum observed for charged particles
Pb-Pb collisions
Non-strange-D-meson $R_{AA}$

- Strong suppression of high-$p_T$ D-meson production in central Pb-Pb collisions.
- Suppression increasing with centrality.
- Similar $R_{AA}$ at 2.76 TeV and 5 TeV
  - Improved precision and high-$p_T$ reach with run-2 data
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• Suppression increasing with centrality.
• Similar $R_{AA}$ at 2.76 TeV and 5 TeV
  • Improved precision and high-$p_T$ reach with run-2 data
  • Expected in models from balancing of denser medium and harder spectrum

**D_s^+-meson R_{AA}**

Pb-Pb, $\sqrt{s_{NN}} = 5$ TeV (run 2)

- Average $D^0$, $D^+$, $D^{**}$
- $D_s^+$

Filled markers: pp rescaled reference
Open markers: pp $p_T$-extrapolated reference

**Hints**

- Hint for $R_{AA}(D_s^+) > R_{AA}$ (non-strange D) at low $p_T$.
- Hint for higher $D_s^+/non$-strange D meson ratio in Pb-Pb than pp collisions, w/o evident centrality dependence

→ Hadronisation via coalescence in a strangeness-rich environment?
**D_{s}^{+}-meson \ R_{AA}**

Pb-Pb, $$\sqrt{s_{NN}}=5 \text{ TeV (run 2)}$$

- **ALICE Preliminary**
  - 0-10% Pb-Pb, $$\sqrt{s_{NN}} = 5.02 \text{ TeV}$$
  - $$|y|<0.5$$

- PHSD, Average $$D^{0}, D^{+}, D^{++}$$
- PHSD, $$D_{s}^{+}$$
- TAMU, Average $$D^{0}, D^{+}, D^{++}$$
- TAMU, $$D_{s}^{+}$$

**Filled markers:** pp rescaled reference

**Open markers:** pp, $$\rho_{\gamma}$$-extrapolated reference

- Average $$D^{0}, D^{+}, D^{++}$$
- $$D_{s}^{+}$$

**Hint for** $\ R_{AA}(D_{s}^{+})>R_{AA}$(non-strange D) **at low** $p_{T}$.  

**Hint for higher** $D_{s}^{+}$/non-strange D meson ratio in Pb-Pb than pp collisions, w/o evident centrality dependence

→ **Hadronisation via coalescence in a strangeness-rich environment?**

- TAMU: PLB 735, 445-450 (2014)
Heavy-flavour decay leptons

- Strong suppression of heavy-flavour decay electrons [muons] at central [forward] rapidity in 0-10% Pb-Pb collisions. Similar results at central and forward rapidity
- Beauty main component from $p_T > 5$ GeV/c (FONLL and pp measurements)
  → indication of beauty suppression at high $p_T$
- Beauty-electron $R_{AA}$ measured directly with impact parameter fit (at 2.76 TeV): indication of suppression for $p_T > 3$ GeV/c
- Hint of $R_{AA}$ (beauty electrons) > $R_{AA}$ (HF electrons): consistent with expectation of smaller energy loss for beauty quarks
Open charm and beauty

At high $p_T$:

\[ R_{AA}(J/\psi \text{ from B}) > R_{AA}(D) \text{ in central collisions} \]

Indication of $R_{AA}(B) > R_{AA}(D)$

The different suppression and the centrality dependence as expected from models with quark-mass dependent energy loss ($\Delta E_g > \Delta E_{lq} \geq \Delta E_c > \Delta E_b$)

Expected from dead cone effect:

\[ \alpha \propto \frac{1}{\left[ \theta^2 + \left(\frac{m_Q}{E_Q}\right)^2 \right]^2} \]

Dokshitzer, Khoze, Troyan, JGP 17 (1991) 1602.
Open charm and beauty

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The different suppression and the centrality dependence as expected from models with quark-mass dependent energy loss

$(\Delta E_g > \Delta E_{lq} \geq \Delta E_c > \Delta E_b)$

Expected from dead cone effect:

\[
\frac{1}{\theta^2 + (m_Q / E_Q)^2} \propto \theta^2
\]


Similar D meson and pion $R_{AA}$

Expected from small charm-quark mass effects + different charm and gluon/light-quark spectrum slope and fragmentation

(e.g. see M. Djordjevic, PRL112 (2014) 042302)
D-meson $v_2$

- Compatible $v_2$ of $D^0, D^+, D^{*+}$.
- D-meson average $v_2$ significantly larger than 0 up to 10 GeV/$c$ charm quarks sensitive to medium collective motion.
- First measurement of $D_s$ $v_2$: compatible with non-strange D-meson $v_2$ within uncertainties.
D-meson $v_2$

- Compatible $v_2$ of $D^0, D^+, D^{*+}$.
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- Similar $v_2$ at $\sqrt{s_{NN}}$=2.76 and 5 TeV.
- D meson and charged pion $v_2$ compatible within uncertainties: hint for smaller $v_2$ of D mesons for $p_T<4$ GeV/c.
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- Similar $D^0$ $v_2$ in 10-30% and 30-50%
**D-meson \( v_2 \) with Event-Shape Engineering**

Event-by-event variation of the flow coefficients \((v_n)\) at fixed centrality can be large

Related to initial-condition fluctuations and event eccentricity

→ Investigate flow vs. 2\(^{nd}\) order reduced \( q \)-vector

\[
q_2 = \frac{|\bar{Q}_2|}{\sqrt{M}}, \quad Q_{2,x} = \sum_{i=1}^{M} \cos 2\varphi_i, \quad Q_{2,y} = \sum_{i=1}^{M} \sin 2\varphi_i
\]

\[
\langle q_2^2 \rangle \approx 1 + \langle M - 1 \rangle \left\langle v_2^2 - \delta_2 \right\rangle
\]

\( \delta \): non-flow effects

\( M \): multiplicity

\( v_2 \): flow strength

*Significant separation* of D-meson \( v_2 \) in events with **large** and **small** \( q_2 \)

Charm sensitive to collectivity of light-hadron bulk, and by **event-by-event initial-conditions fluctuations**
**Comparison to models (2)**

**High $p_T$: region dominated by radiative energy loss**

PQCD-based models provide a fairly good description

<table>
<thead>
<tr>
<th>pQCD e-loss MODELS</th>
<th>Collisional energy loss</th>
<th>Radiative energy loss</th>
<th>Recombination</th>
<th>Hydro</th>
<th>nPDF</th>
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Comparison to models (1)

Low $p_T$: fairly good description with transport models → important role of recombination and elastic scatterings

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<th>Collisional energy loss</th>
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</tbody>
</table>

Courtesy of E. Bruna
Comparison to models (3)

• Models able to reproduce $v_2$ favour diffusion coefficient $2\pi TD_s(T)$ in the range 1.5-7 at $T_c$ with a corresponding thermalisation time $\tau_{charm}=3$-$14$ fm/c.

• Powerful constraints by considering complementary observables ($R_{AA}$ and $v_2$ of non-strange D and D$_s^+$) over wide $p_T$ ranges and in different centrality classes.

More by M. Nahrgang (next talk)
Plans for run 3 and run 4

Detector upgrade (LS2) → improve data precision, extend $p_T$ range, new observables, in particular D meson down to $p_T=0$, B mesons, heavy-flavour baryons in Pb-Pb.

→ Deeper understanding of heavy-quark interaction with the QGP constituents

→ Allows for determination of transport coefficients and diffusion coefficients

... and tremendous boost for HF jets, HF correlations, event-shape-engeneering, studies as a function of event multiplicities in small systems, ...
First steps towards the study of heavy-flavour jet production and properties
Charm jet production in pp and p-Pb collisions

- Charm jets **tagged by the presence of a fully reconstructed D meson**
- D-jet spectrum measured from $p_T=5$ GeV/$c$ to 30 GeV/$c$ $\rightarrow$ low $p_T$ reach!
- Described by POWHEG+PYTHIA6 (Perugia 2011 tune) simulation within uncertainty
- Data uncertainty smaller than theoretical ones
- Promising for future measurements on larger samples (pp) and in Pb-Pb collisions
  - Unique opportunity to study charm jet properties and structure
Azimuthal correlation of D mesons and charged particles: described by PYTHIA6 Perugia tunes, PYTHIA8 and POWHEG+PYTHIA after baseline subtraction
• p-Pb results in agreement with those measured in pp at 7 TeV (EPJC 77 245 (2017))
• Calibrated tool to investigate possible modification of charm jet properties in Pb-Pb
**HF-decay electron correlation with charged particles in Pb-Pb collisions**

**Near-side yield:**

\[
\frac{N_{\text{coll}}}{N_{\text{d}}(\Delta \phi)} = \frac{1}{N_{\text{d}}(\Delta \phi)}
\]

**Pb-Pb collisions**

\[
\Delta \phi (\text{rad})
\]

**Near-side**

- \(c, b\) → e-charged particles \(\Delta \phi\) distribution
- \(4 < p_T^{\text{HF,le}} < 12 \text{ GeV/c}, 1 < p_T^{\text{assoc}} < 2 \text{ GeV/c}\)
- \(|\Delta \eta| < 1\)

**Pb-Pb**

- 0-20% Pb-Pb

**p-Pb**

- 0-20% central

**Hint for an enhancement of associated yield of low-\(p_T\) particles in central Pb-Pb collisions w.r.t. p-Pb collisions**

**Similar to \(\pi^0\)-hadron**

(PLB 762 238-250 (2016))

**ALICE Preliminary**

- \(\sqrt{s_{NN}} = 5.02 \text{ TeV}\)

**Near-side yield:**

- \(Y_{\text{Pr-Pb}/Y_{p-Pb}}\)

**ALICE Preliminary**

- \(4 < p_T^{\text{le}} < 12 \text{ GeV/c}\)
- \(|\Delta \eta| < 1\)
- \(|\Delta \phi| < 0.8\)

**HF electron as “trigger” particle**

**Underlying event**

- ALICE, 0-10% Pb-Pb, \(\sqrt{s_{NN}} = 2.76 \text{ TeV}\)
- \(8 < p_T^{\text{n}} < 16 \text{ GeV/c}\)
- Near side (\(|\Delta \eta| < 0.7\))

- \(\pi^0\)-hadron (v, bkg)
- AMPT model
- JEWEL model
Conclusion

Proton-proton
• D-meson production in proton-proton collisions described by pQCD over a wide momentum range (down to $p_T=0$): theoretical uncertainties much larger than data ones.
• $\Lambda_c^+,\Xi_c^0$-baryon production underestimated by models: do we have charm hadronisation under control?

Proton-Pb
• D-meson $R_{\text{pPb}}$ compatible with unity $\rightarrow$ “small” effects from CNM (or QGP in p-Pb)
  • Crucial to improve precision at low $p_T$ $\rightarrow$ new pp reference (2017)
• Hint for $Q_{\text{CP}} > 1$
• Positive $v_2$ of HF-decay electrons

Pb-Pb
• Significant D-meson suppression $\rightarrow$ significant charm energy loss
• Indication for $R_{\text{AA}}(D) < R_{\text{AA}}(B)$ $\rightarrow$ mass-dependent energy loss
• Hint for $R_{\text{AA}}(D_s^+) > R_{\text{AA}}$(non-strange D) $\rightarrow$ hadronisation via coalescence?
• Significant charm flow observed: hint for $v_2(D) < v_2(\pi^+)$ below 4 GeV/c

$\rightarrow$ Charm quarks strongly interact with the medium and are influenced by its collective motion
$\rightarrow$ Further support for hadronisation via coalescence?
• Improved precision from run-2 data allows to set important constraints for models describing charm $R_{\text{AA}}$ and $v_2$.

Next, run 2: improve precision with data from incoming pp run at 5 TeV and 2018 Pb-Pb run
run 3,4: “precision era” for charm an beauty
Conclusion

Proton-proton

• D-meson production in proton-proton collisions described by pQCD over a wide momentum range (down to $p_T=0$): theoretical uncertainties much larger than data ones.
• $\Lambda_c^+,$ $\Xi_c^0$-baryon production underestimated by models: **do we have charm hadronisation under control?**

Proton-\(\text{Pb}\)

• D-meson $R_{\text{pPb}}$ compatible with unity à “small” effects from CNM (or QGP in \(\text{p-Pb}\))
• Crucial to improve precision at low $p_T$ à new \(\text{pp}\) reference (2017)
• Hint for $Q^\text{CP}>1$
• Positive $v_2$ of HF-decay electrons

Pb-Pb

• Significant D-meson suppression à significant charm energy loss
• Indication for $R_{\text{AA}}(D)<R_{\text{AA}}(B)$ à mass-dependent energy loss
• Hint for $R_{\text{AA}}(D_s^+ +) > R_{\text{AA}}(\text{non-strange D})$ à hadronisation via coalescence?
• Significant charm flow observed: hint for $v_2(D)<v_2(\pi^+)$ below 4 GeV/c à Charm quarks strongly interact with the medium and are influenced by its collective motion à Further support for hadronisation via coalescence?

• Improved precision from run-2 data allows to set important constraints for models describing charm $R_{\text{AA}}$ and $v_2$ D-meson data (RHIC and LHC run 1) used to constrain diffusion coefficient with a Bayesian model-to-data analysis

\[ R_{\text{AA}} \text{ and } v_2 \text{ D-meson data (RHIC and LHC run 1) used to constrain diffusion coefficient with a Bayesian model-to-data analysis} \]

It will be a long journey … but (hopefully) rewarding

Run 3,4: “precision era” for charm and beauty

Y. Xu, M. Nahrgang et al, arxiv 1704.078001v1
Extra
D-meson $v_2$ with Event-Shape Engineering

New promising testing ground for theoretical models

P. Gossiaux et al., arXiv:1705.02271
Production vs. centrality

- Heavy-flavour electron QCP compatible with unity
- Consistent with D-meson result once decay kinematics is taken into account
Heavy-flavour reconstruction with ALICE

Heavy-flavour hadron decay leptons:
- Electrons at mid rapidity ($|y|<0.9$)
  - electron identification with TPC, TOF, ITS, TRD, EMCAL
  - Non-HF electrons (mainly gamma-conversion and $\pi^0, \eta$ Dalitz decay) removed
    1) statistically with data-tuned cocktail
    2) by finding the “partner” with $e^+e^-$ invariant mass technique
- Muons at forward rapidity (-4<$$\eta$$<-2.5) with muon spectrometer:
  - Tracks matched with trigger
  - Subtraction of muons from primary $\pi,K$ decays via simulations with data-tuned $\pi,K$ abundances

Charmed hadron reconstruction ($|y|<0.9$)
Invariant mass analysis of reconstructed hadronic decays:
$D^0 \rightarrow K^-\pi^+$, $D^{*+} \rightarrow D^0\pi^+$, $D^+ \rightarrow K^+\pi^+\pi^+$ $D^+_s \rightarrow \phi\pi^+$, $\phi \rightarrow K^-K^+$
$\Lambda_c^+ \rightarrow pK^-\pi^+$, $\Lambda_c^+ \rightarrow pK^0_s$

Displaced secondary vertices ($\rightarrow$ ITS)
+ PID (p/K/$\pi$ separation with TOF+TPC)

... and semi-leptonic decays (no decay vertex reco)
$\Lambda_c^+ \rightarrow e^+\Lambda\nu$, $\Lambda \rightarrow p\pi^-$
$\Xi_c^0 \rightarrow e^+\Xi^-\nu_e$, $\Xi^- \rightarrow \pi^-\Lambda$

ALICE charged particles

Int. J. Mod. Phys. A 29 (2014) 1430044
More details on $D^0$ reconstruction

2 techniques
-- “Standard” with decay vertex reconstruction: topological selection to reject background → higher S/B, lower selection efficiency (see backup)

-- (D$^0$ only) Analysis w/o vertex reconstruction: yield extraction with background invariant mass distribution estimated with several techniques (event mixing, track rotation, like-sign, direct fit), better precision for $p_T<1$ GeV/c (short decay length)

$\rightarrow D^0$ cross section measured down to $p_T=0$ (so far in pp at $\sqrt{s}=7$ TeV and p-Pb at $\sqrt{s_{NN}}=5$ TeV)
The ALICE detector

Central barrel (|\eta|<0.9, B=0.5 T)
Track and vertex reconstruction (TPC, ITS)
Particle Identification

EMCAL

-4<\eta<-2.5 (2°<\theta<9°)

DCAL

TOF

ITS

TPC

Topological layout of the ALICE detector components:

- **TPC**
- **TOF**
- **ITS**
- **DCAL**
- **EMCAL**
- **MUON SPECTROMETER**

**Data**:

- **p-Pb**
  - \( p_{\text{lab}} = 5.02 \text{ TeV} \)
  - 1.5 < p < 1.6 (GeV/c)

**PID**:

- Hadron rejection factor: 185
- Electron efficiency: 0.86

**Graphs**:

- Distribution of particles in TPC and TOF
- PID efficiency

**Equations**:

- \( -1 \sigma < (\text{TPC } dE/dx - <\text{TPC } dE/dx>) < 3 \sigma \)
- \( (\text{TPC } dE/dx - <\text{TPC } dE/dx>) < -4 \sigma \)
## ALICE data-taking in Run-2

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<th>System</th>
<th>Year</th>
<th>$\sqrt{s_{NN}}$ (TeV)</th>
<th>$L_{int}$</th>
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<td>pp</td>
<td>2015-2016</td>
<td>13</td>
<td>~14 pb$^{-1}$</td>
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<tr>
<td>pp</td>
<td>2015 (~4 days)</td>
<td>5.02</td>
<td>~100 nb$^{-1}$</td>
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</tr>
<tr>
<td>Pb-p</td>
<td>2016</td>
<td>8.16</td>
<td>~20 nb$^{-1}$</td>
</tr>
<tr>
<td>Pb-Pb</td>
<td>2015</td>
<td>5.02</td>
<td>~0.4 nb$^{-1}$</td>
</tr>
</tbody>
</table>

- Goals for 2017-18:
  - Pb-Pb: reach 1/nb target
  - pp 13 TeV: reach 40/pb target
  - High statistics pp 5 TeV sample
Recent results in pp collisions

Important constraints for theoretical calculations
D-meson yields vs. multiplicity: comparison with models (pp)

**Percolation** (Ferreiro, Pajares, PRC 86 (2012) 034903)
Particle production via exchange of colour sources between projectile and target (close to MPI scenario)
- Faster than linear increase

**EPOS 3.099** (Werner et al., PRC 89 (2014) 064903)
Gribov-Regge multiple-scattering formalism
Saturation scale to model non-linear effects
Number of MPI directly related to multiplicity ➔ slightly faster than linear
With hydrodynamical evolution applied to the core of the collision ➔ faster than linear increase

Soft-QCD tune
Colour reconnection
MPI ➔ Linear increase
Charm-particle species ratios (pp)

- D-meson species relative abundances as expected from theory, including $D_s$/non-strange $D$.
- $\Lambda_c^+/D^0$ and $\Xi_c^0/D^0$ higher than theoretical expectations (large uncertainties)
  → Is charm hadronisation understood?
  → Need to reduce experimental uncertainties to provide more precise input to models
Charmed baryons in pp and p-Pb

- $\Lambda_c$ production cross section higher than theoretical expectations
- $R_{pPb}$ compatible with unity, with D meson $R_{pPb}$, with pQCD+nPDF, as well as with a model assuming QGP formation in p-Pb
Charm jet properties: D-h correlations

- Azimuthal correlation of D mesons and charged particles: described by PYTHIA6 Perugia tunes, PYTHIA8 and POWHEG+PYTHIA
- p-Pb results in agreement with those measured in pp at 7 TeV (EPJC 77 245 (2017))
Charm jet properties: D-h correlations

Similar correlation functions in pp at 7 TeV (EPJC 77 245 (2017)) and p-Pb at 5.02 TeV, after baseline subtraction
D$^0$-tagged jet in pp: detector performance

ALICE Simulation, PYTHIA6, pp, $\sqrt{s} = 7$ TeV
Charged Jets, Anti-$k_T$, $R=0.6$, $|\eta_{jet}|<0.3$ with $D^0 \rightarrow K\pi^+$ and c.c.
$0.2 < z_{det} < 1.0, 1 < p_{T,D} < 30$ GeV/c

Mean $p_T$ resolution $\sim 11\%$

Jet $p_T$ resolution $\sim 3\%$
In events with a selected D-meson candidate, jets are reconstructed replacing the D meson daughters with the reconstructed D-meson particle.

D-jets = jets with D-meson as one of the constituents

Spectrum of real D-jets obtained by subtracting the spectrum of jets with background D in the invariant mass sidebands from the spectrum in the D mass peak

Correction for efficiency

Feed-down subtraction based on POWHEG+PYTHIA simulations and efficiencies

Integrate over D-meson $p_T$ bins

Unfolding for detector effects and underlying event fluctuations in p-Pb collisions
D-jets in pp collisions

D-jet spectrum measured from $p_T=5$ GeV/c to 30 GeV/c
Main syst. uncertainties: yield extraction, feed-down subtraction, unfolding
Described by POWHEG+PYTHIA6 (Perugia 2011 tune) simulation within uncertainty
ATLAS $D^+$-jet measurement in pp collisions

$R(\rho, z) = \frac{[D^+\text{-jet } (p_T, z) \text{ yield}]}{[\text{inclusive-jet yield } (p_T)]}$

$z = \frac{D^+ \text{ momentum along the jet direction}}{\text{jet energy}}$

$R(D^+\text{-jet/inclusive jets}) = 0.025 \pm 0.001^{(\text{stat.})} \pm 0.004^{(\text{syst.})}$ (for $0.3 < z < 1$, $|\eta| < 2.5$, $25 < p_T < 70 \text{ GeV/c}$)

- $D^+$-jet production w.r.t. inclusive jet production underestimated by models at low $z$
- Larger discrepancy at lower $p_T$
Positive $v_2$ of HF electrons in semi-central 20-40% Pb-Pb collisions at 2.76 TeV. $v_2$ tends to increase from central to semi-central collisions.

Similar $v_2$ at mid-rapidity [electrons] and forward rapidity [muons].

Similar $v_2$ at $\sqrt{s_{NN}}=2.76$ and 5 TeV
QGP tomography with heavy quarks

- Early production in hard-scattering processes with high $Q^2$
- Production cross sections calculable with pQCD
- Strongly interacting with the medium
- Hard fragmentation $\Rightarrow$ measured meson properties closer to parton ones

$\text{“Calibrated probes” of the medium}$

Study parton interaction with the medium
- energy loss via radiative ("gluon Bremsstrahlung") collisional processes
  - path length and medium density
  - color charge (Casimir factor)
  - quark mass (e.g. from dead-cone effect)

Figure from A. Andronic et al., EPJC C76 (2016)

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- participation in collective motion $\Rightarrow$ azimuthal anisotropy of produced particle

at all $p_T$ for charm and beauty (large masses $>> \Lambda_{QCD}$)
**D$^+_s$/D$^+$ ratio vs. multiplicity**

In pp and p-Pb no evidence of modification of D$^+_s$/D$^+$ ratio